Reliability Analysis of Condition Monitoring Network of Wind Turbine Blade Based on Wireless Sensor Networks

Zhixin Fu, Yang Luo, Chenghong Gu, Furong Li, Yue Yuan

Abstract**—**This paper proposes a reliability analysis method for the condition monitoring network of wind turbine blade based on wireless sensor networks. Two critical factors which play significant roles in the reliability evaluation of the monitoring network are focused on, that is, the reliability of sensor nodes and the reliability of communication links. Firstly, with the established reliability models for sensor nodes and communication links, the method of establishing reliability simulation model of monitoring network is presented based on Monte Carlo method. Secondly, according to the analysis of the intra-cluster reliabilities of the tree topology and the mesh topology, the topology selection principle of the sensor network for a single blade is proposed. Finally, the influence of maintenance cycle and communication interference on the overall reliability of the monitoring network is illustrated and the proper maintenance cycle is achieved. The solution to communication interference is put forward with the data retransmission measure. The overall reliability of the network is improved effectively by adopting the one-time data retransmission measure. Our work is expected to provide the guidance in theory and technology for constructing the high-performance condition monitoring and control system for wind turbine blades.

Index terms**—**wind turbine blade; monitoring network; reliability; Monte Carlo methods; data retransmission

I. INTRODUCTION

BLADE is the power source of the wind turbine whose operational reliability directly affects the whole performance of the wind turbine. During the operation of the wind turbine, the blade is prone to various and complex failures. Once the failure accident occurs, the wind turbine must be shut down and repaired, the maintenance cost and economic loss caused by the downtime are enormous [1]. Therefore, the research on the blade condition monitoring is of practical significance. The information processing ability of the Wireless Sensor Network (WSN) is powerful which can easily obtain the physical information of the monitoring area in real time. At present, wireless sensor network technology has been widely used in various monitoring fields, such as climate monitoring, medical monitoring, building structure monitoring, and so on. Only a limited number of sensor nodes need to be deployed in the blade monitoring network and wireless communication method is adopted. Compared with the widely used wired communication method, wireless communication method can be adopted without the network infrastructure establishment. Furthermore, the network layout and adjustment are more flexible. Thus, the wireless communication method is easier to be implemented, which provides a useful reference for the wind turbine blade condition monitoring [2-5]. In [6], the feasibility of the application of WSN in wind turbine condition monitoring is proposed. The hardware design of sensor nodes and the hardware and software designs of the whole monitoring network are provided. Real-time damage detection algorithms can be used with sensor network for online

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condition monitoring. For example, a novel automated structural change detection algorithm is presented in [7]. The algorithm is principally based on a windowed Hilbert–Huang transform of online data and incorporates a combination of energy based averaging and moving window averaging. The system has been implemented on a wireless sensor platform. In [8], establishing *K* reliability model is proposed, which defines the reliability of the monitoring network as the probability that any point in the region is covered by *K* valid nodes. In [4], the corresponding sensors are deployed according to the different failure types of the wind turbines and the cluster-based distributed wireless sensor network topology is proposed to improve the reliability of the monitoring network. In [9], the residual energy of sensor node is selected as the selection criterion of the cluster head node so as to improve the reliability of the monitoring network.

Based on the above analyses, it is far from enough to meet the application requirements simply by providing the monitoring network for wind turbine blades. Obviously, the reliability of the monitoring system is critical to obtain the condition information of wind turbine blades accurately and in real time. Therefore, it is essential to study the reliability of the monitoring network. Although some excellent results have been yielded in existing research, several key issues affecting the reliability of the monitoring network should be given a further discussion. For one thing, due to the severe environment condition of the wind turbine, it is inevitable for the sensor nodes to break down during the run time. However, the case of the sensor node failure is not considered in existing study. For another, the reliability of communication links of the monitoring network is not involved which directly determines the success of the communication between the monitoring network and the control center. Focusing on the above problems, a reliability analysis method of the condition monitoring network of wind turbine blades is presented in this paper. Firstly, the reliability sub-models of sensor nodes, the reliability sub-models of communication links and the multi-task-completed models of monitoring network are established and the method of establishing reliability simulation model of monitoring network is presented based on Monte Carlo method. Then, the topology selection principle of sensor network for a single blade is proposed by the simulation of the intra-cluster reliability of the sensor network for a single blade with the tree topology and the mesh topology. Finally, the influence of the maintenance cycle and communication interference on the overall reliability of the monitoring network is analyzed, and the overall reliability of the monitoring network is improved by one-time retransmission measure. Our work is expected to provide the guidance in theory and technology for constructing the high-performance condition monitoring and control system for wind turbine blades.

II. TOPOLOGY OF THE MONITORING NETWORK

A single wind turbine usually has three blades, and sensor nodes of the monitoring network should be deployed on the blades to collect and transmit the condition information. If the condition information acquired by sensor nodes on each blade is fused separately, the operation condition of the blade can be reflected more comprehensively. In view of this, in this paper, a hieratchical-clustered topology is adopted as the overall structure of monitoring network. The advantages of this topology are the following: ① Excellent network extensibility and convenient deployment. The type, location and number of nodes can be determined according to the actual application requirements. ② A cluster represents a set of stress sensor nodes in the adjacent area. Sensor nodes form several independent clusters. The cluster head node of each cluster are responsible for receiving and processing the information acquired by the intra-cluster nodes and sending it to the base station, which can greatly reduce the data communication pressure, improve the information processing efficiency and enhance the network reliability. The design of the deployment of sensor nodes on a single blade is shown below.

In this paper, the reliability of the wind turbine blade condition monitoring network is analyzed with the blade of the type of TG41.0G [10]. This type of wind turbine blades is produced by Jiangsu Miracle Logistics System Engineering Co., Ltd., China which has been applied to many practical wind farms in China. The research shows that the main load-bearing structure of wind turbine blade is the main beam, therefore, the sensor nodes are deployed on the main beam along the blade extension. For the convenience of the research, the blades are divided into upper and lower parts, shown in Fig.1. The sink node is installed on the wind turbine foundation.

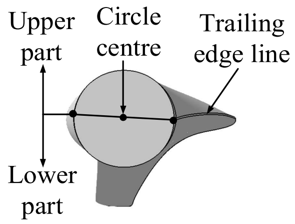

Fig.1 The division of the upper and lower parts of a blade

The structure of the condition monitoring network of the wind turbine blade is shown in Fig.2. The monitoring network consists of M stress sensor nodes (hereinafter referred to as sensor nodes), one sink node and one control centre. The sensor nodes are responsible for the acquisition and transmission of the stress on the blade. The sensor nodes on each blade are divided into one cluster, therefore, there are three clusters in the monitoring network for all the three blades. The cluster head nodes receive the stress information from intra-cluster nodes and transmit it to the sink node. Then, the sink node transmits the information to the control centre. Finally, the control centre judges the blade condition according to the acquired information and provide the beneficial reference for the operation and maintenance of each blade.

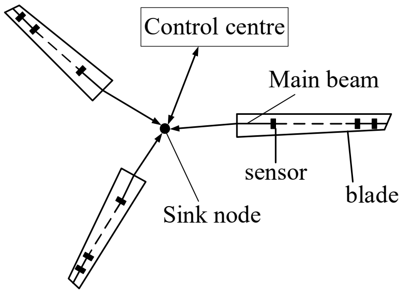

Fig.2 Topology of the monitoring network

III. RELIABILITY MODELLING

Reliability is a crucial evaluation criteria for the monitoring network performance of wind turbine blades, which can be effectively analysed by establishing a reasonable reliability model. Through reliability analysis, the factors that affect the reliability of the condition monitoring network can be found out conveniently, which are of great significance for the monitoring network improvement. In this paper, the reliability sub-models of sensor nodes, the reliability sub-models of communication links and the multi-task-completed models of monitoring network are established. Then, the reliability evaluation method of monitoring network is presented based on Monte Carlo method.

A. Reliability sub-model

The reliabilities of sensor nodes and communication links play significant roles in evaluating the reliability of the condition monitoring network of the wind turbine blade. The limited battery power and the computational capacity are primary restrictions of the reliability of sensor nodes. The reliability of wireless communication links is mainly restricted by several factors, including failure sensor nodes, communication bandwidth, delay, error rate and data packets.

Because it is the stress sensors' responsibilities to collect the initial monitoring information and transmit the information to the cluster head nodes, the sink node, finally to the control centre, the stress sensor nodes are the most important basic factor to establish the monitoring network. Meanwhile, compared with the number of cluster head nodes, sink nodes and control centre, the number of the stress sensors is the largest in the monitoring network. Therefore, the reliability of the stress sensor nodes is the key factor for the reliability of the whole monitoring network. However, considering the cost of stress sensor nodes in the practical application and the convenience of the installation, the function and volume of the stress sensor nodes should be restricted. Therefore, the failure of the stress sensors must frequently occur in the adverse operating environment of the wind turbine. However, the stress sensor nodes are deployed on the blade, so it is very inconvenient to repair or replace them. The number of the cluster head nodes, sink node and control centre is very small, so they can be respectively deployed in the wind turbine blade, the wind turbine foundation and the wind farm. Compared with stress sensor nodes, their volumes are almost unrestricted and their functions can be more powerful. It is relatively easier to repair or replace these components when there are some problems with them. Therefore, the failure of stress sensor nodes, and failures of communication links between stress sensor nodes, the stress sensor node and the cluster head are focused on in this paper. For the convenience of analysis, the following assumptions are proposed when the reliability model of the condition monitoring is established:

a) Sensor nodes, communication links and sink nodes are only in normal or failure condition.
b) The working states of sensor nodes and sink node are independent to each other, that is, when a node is in the normal or failure state it will not affect all other nodes.
c) The same type of nodes in the monitoring network obey the same lifetime probability distribution function.

d) The cluster head nodes, sink node will not fail. The communication link between sink node and cluster head node, while the communication link between sink node and control centre will not fail either.

1) Reliability sub-model of sensor nodes

The reliability of a sensor node can be easily reflected by its lifetime. At present, the lifetime of a sensor node mainly obeys exponential distribution, binomial distribution and Weibull distribution. Weibull distribution is the most widely used in lifetime test and reliability analysis [11]. Therefore, in our work the Weibull distribution function is used as the probability distribution function of sensor nodes [12]. Therefore, the reliability function of a sensor node is defined by eq.(1):

$$G_\sigma(t) = 1 - F_\sigma(t) = e^{-(t/\lambda)^k} \tag{1}$$

Where t is the operating time of a sensor node; λ is the scale parameter of Weibell distribution; k is the shape parameter and its value is determined by the type and characteristics of the sensor node. $F_\sigma(t)$ is the probability that the lifetime of a sensor node is less than t, that is, the failure rate. The values of λ and k can be obtained by parmhat=wblfit (data) function in MATLAB R2014a and "data" represents sample values.

Let T be the maintenance cycle of the monitoring network and t_i be the lifetime of sensor node i. Then the node condition in the maintenance cycle can be defined by eq.(2):

$$X(i) = \begin{cases} 0, & t_i \ge T, \text{ Node is normal} \\ 1, & t_i < T, \text{ Node fails} \end{cases} \tag{2}$$

2) Reliability sub-model of communication links

In the monitoring network of wind turbine blade, the communication links are usually subject to the external interference due to the wireless communication, which are prone to lead to the problems of packet loss, error code and so on. Thus, the information acquired by the control center might be inaccurate. Therefore, the reliability of communication links cannot be neglected in the reliability modeling of monitoring network. In our work, the reliability evaluation model of wireless communication links is given as follows.

Let the physical information acquired by a sensor node at a time be a data frame with a length of l and P_{bit} be the bit error rate of data transmission.

When the nodes of transmitting end and receiving end are both normal, the reliability function f of the information transmission can be defined by eq.(3):

$$f = (1 - p_{\text{bit}})^l \tag{3}$$

The failure rate of each link in the maintenance period is P which is uniformly distributed in [0,1]. If two sensor nodes, i and j, are the transmitting end and receiving end respectively and the communication link K between i and j exists, the condition of communication link K can be defined by eq.(4):

$$L(k) = \begin{cases} 0, & 0 \le P < f, \text{the link is normal} \\ 1, & P \ge f, \quad \text{the link fails} \end{cases} \tag{4}$$

B. Multi-task-completed modeling

In the condition monitoring network of wind turbine blade, the states of sensor nodes and communication links changes dynamically, so the network condition should be evaluated dynamically to obtain the completion situation of the monitoring tasks. In this paper, a multi-task-completed model of the monitoring network is established. Meanwhile, the question of multi-task condition evaluation of monitoring network is transformed into the question of reachability of sensor nodes communication in the network. Warshall algorithm [13] is used to solve the multi-task reachability matrix to obtain the completion situation of tasks of the monitoring network.

1) Task modeling

Let $T_{S,L}$ be the task of condition monitoring network of the wind turbine blade. $T_{S,L}$ consists of binary set [S, L]. $T_{S,L}$ refers to the task whose source node (sensor node) is S while the destination node is L.

Definition: A single task of the monitoring network, that is, a sensor node acquires the physical information and transmits the information to the cluster head node or the sink node.

The task $T_{S,L}$ can rely on either a transmission path or multiple redundant paths. The reliability of the information transmitted in the transmission path $T^i_{S,L}$ of task $T_{S,L}$ depends on the set $J^i_{S,L}$ of nodes and the set $C^i_{S,L}$ of communication links contained in the path. The success of data transmission in the path i requires all nodes and communication links in the path to be in normal working condition.

The working condition of the transmission path i of task $T_{S,L}$ in the maintenance cycle can be defined by eq.(5):

$$X^i_{S,L} = \prod_{j=1}^{a} X(j) \cdot \prod_{k=1}^{b} X_l(k) \tag{5}$$

Where a and b respectively represent the number of nodes in the node set and the number of the communication links in the i-th transmission path.

2) Multi-task-completed model

The completion situation of each task can be achieved when the working conditions of all sensor nodes and communication links in the condition monitoring network are known. Because the condition of sensor nodes and communication links possibly turn to failure, the network topology changes dynamically. To adapt to this characteristic, the Warshall algorithm is adopted to solve the multi-task reachability matrix of the monitoring network in our work. The completion situation of the network task is achieved by reachability matrix.

Adjacency matrix and reachability matrix in graph theory can be used to solve the communication path routing problem in networks [14-16]. The network vertex number is M. The network is the oriented graph: $D=(V, E)$, the vertex set: $V=(v_1,v_2,v_3,\cdots,v_M)$, the link set: E.

The adjacency matrix A of the network is defined by eq.(6):

$$A = (a_{ij})_{M \times M} \tag{6}$$

Where a_{ij} is the number of edges between v_i and v_j.

The reachability matrix $Y=(y_{ij})_{M\times M}$ of the network is defined by eq.(7):

$$y_{ij} = \begin{cases} 0, & v_i \text{ and } v_j \text{ are unreachable} \\ 1, & v_i \text{ and } v_j \text{ are reachable} \end{cases} \tag{7}$$

In the formula, that v_i and v_j are reachable represents the information of the node v_i can be transmitted to the node v_j, otherwise they are unreachable.

At present, the general algorithm and the Warshall algorithm are two main algorithms for solving the reachability matrix. The solving idea of the general algorithm is as follows: first, solve the eq.: $B_{M\times M}=A+A^2+\ldots+A^M$; then, change the elements that are not 0 in the matrix $B_{M\times M}$ to 1 and the elements of 0 are unchanged. The obtained matrix is the reachability matrix. It is more complex to calculate the reachability matrix by the general algorithm mainly because of the complexity of the calculation of $B_{M\times M}$. In the Warshall algorithm, the adjacency matrix is regarded as the relation matrix. So solving the reachability matrix is equivalent to solving the positive closure of the adjacency matrix. Therefore, the reachability matrix can be solved according to the method of solving the relation closure in the set theory more conveniently. The Warshall algorithm is used to calculate the reachability matrix of the monitoring network in this paper. And the steps of solving the reachability matrix are the followings.

Step 1: A is taken as the initial value of the reachability matrix Y. The conditions of all nodes and communication links in the monitoring network are evaluated. If one node fails, the row and column elements where the node is in Y are set to 0. If one communication link fails, the corresponding element in the Y is set to 0. Then the adjacency matrix of the monitoring network is obtained.

Step 2: $i\leftarrow 1$.

Step 3: for all the j ($1\le j \le M$), if $a_{ji}=1$, for each k(k=1, 2, 3, $\cdots$, M), add logically A[j,k] to A[i,k] and send the result to A[j,k]. that is, if $a_{ji}=1$, A[j,k]←A[j,k] V A[i,k], and if A[j,i]=0, j←j+1.

Step 4: $i=i+1$.

Step 5: if $i \le M$, turn to step 3. Otherwise, stop it and output the reachability matrix Y, $Y=A$.

The flowchart of solving reliability matrix has been shown in Fig.3.

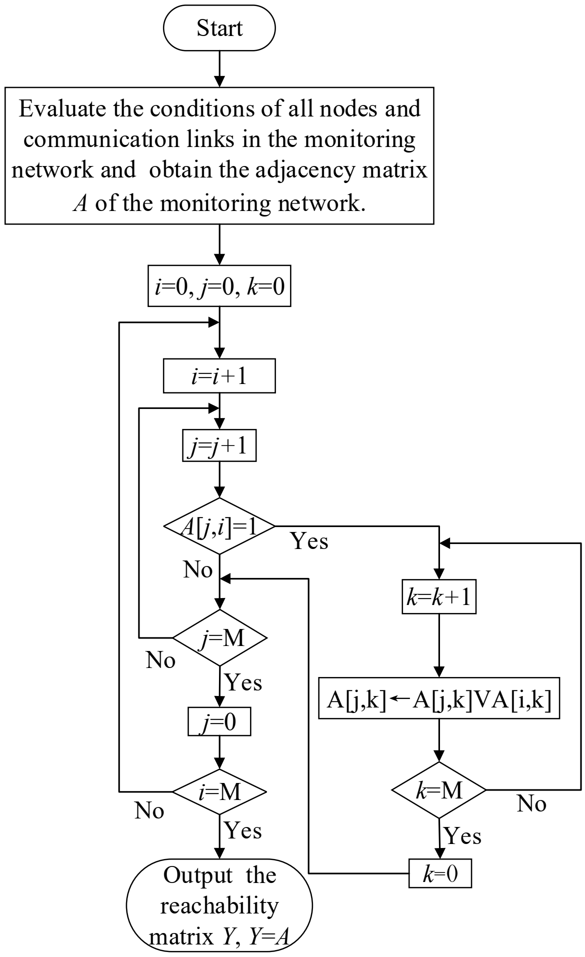

Fig.3 Flowchart of solving reliability matrix

In the condition monitoring network of the wind turbine blade, any sensor node and cluster head node or sink node form a single task. Because the monitoring network is composed of multiple sensor nodes, the monitoring network operates in the multi-task mode. For a monitoring network composed of m sensor nodes, the data of m nodes are acquired and converged in a transmission task, therefore, the total number of the monitoring network tasks is m. Taking the sensor nodes as the source nodes and cluster head nodes or the sink node as the destination node, the connection situation of any two nodes of the monitoring network in the actual operating condition can be obtained by solving the reachability matrix. Let n be the number of tasks that can be completed by the monitoring network in one transmission, then the completion rate of the network tasks is defined by eq.(8):

$$\theta = \frac{n}{m} \times 100\% \tag{8}$$

According to the reliability requirements of the monitoring network of the wind turbine blade, the reliability evaluation criteria of the monitoring network is defined as follows in our work. In one transmission, if 20% of the sensor data cannot be transmitted to the control center, that is, θ < 80%, the monitoring network is considered to fail, otherwise normal. It should be noted that this is not an industrial standard. The wind turbine condition monitoring technology based on wireless sensor network is still in the process of the theoretical analysis. It has not been applied in practice. The set index is for the convenience of the illustration that how to establish the reliability model and analyse the reliability of the monitoring network by the reliability model. The reliability evaluation index can be set flexibly according to different application situations. In this paper, the critical value 80% is set only for clearly explaining the reliability analysis process.

C. Reliability simulation model based on Monte Carlo method

Considering the complexity of the operation condition of the monitoring network, the reliability of the monitoring network should be analyzed properly before use to achieve the optimized design scheme of the monitoring network with higher reliability. In our work, the sampling method of condition duration of the sensor nodes and the condition of the communication links is proposed firstly. Then the method of establishing the reliability simulation model of the monitoring network is put forward by Monte Carlo method.

1) The sampling of condition duration of the sensor nodes

The failure rate of a sensor node changes dynamically over time. The lifetime probability function is defined by eq.(1). The state duration of a sensor node from the initial normal state to the first failure can be achieved by solving the inverse function of eq.(1). In view of the dynamic variation of the reliability of sensor nodes, the sampling method of state duration of sensor nodes is adopted, that is, sample the state duration of sensor nodes randomly after the initial state is selected. The initial state of sensor nodes is set to be normal. G_σ is uniformly distributed in [0,1], then the condition duration of the sensor node i can be described as eq.(9):

$$t_i = \lambda \cdot \sqrt[k]{-\ln G_\sigma} \tag{9}$$

2) The condition sampling of communication links

The reliability function of information transmission of the communication links is $f = (1 - p_{bit})^l$. The failure rate of each link in the maintenance period is P, and P is uniformly distributed in [0,1].

3) Reliability simulation model based on Monte Carlo method

In our work, the reliability of the monitoring network is simulated by the software MATLAB R2014a based on Monte Carlo method [17]. The states of all sensor nodes and communication links can be obtained in each simulation, thus the real-time topology of monitoring network can be achieved. According to the real-time topology, the adjacency matrix is established and the reachability matrix can be worked out by Warshall algorithm. Then the reliability of monitoring network can be achieved. The steps are as follows:

Step 1: Set N_S be the total simulation number of times of the wind turbine blade monitoring network and T be the maintenance cycle of monitoring network. The initial operating states of each node and link in the monitoring network are normal and the sensor batteries are full of energy. The number of Monte Carlo simulation is j, the number of sensor nodes in the monitoring network is m and the number of monitoring network failures in the simulations is N_f. Initially, j=0, N_f=0;

Step 2: At the beginning of simulation, the states of sensor nodes and communication links are normal. $j=j+1$.

Step 3: The state duration t_{ij} of the sensor nodes and the failure rate P of the wireless communication links are achieved by random sampling.

Step 4: Judge the states of sensor nodes and communication links. For the sensor nodes, if $t_{ij} \geq T$, the state of the sensor node i in the j-th simulation is normal, x_{ij}=0, otherwise, x_{ij}=1. For the communication links, that each element of adjacency matrix of the monitoring network is not equal to 0 represents the communication link exists from node i to node j. If $P \geq f$, the link fails.

Step 5: According to the states of sensor nodes and communication links achieved by sampling, the failure nodes and failure links are eliminated. Then the adjacency matrix of the network is re-established.

Step 6: Solve the reachability matrix of monitoring network with Warshall algorithm. In the reachability matrix, the sum of elements in the column of the destination node minus the corresponding elements of the destination node is the number of the completed tasks. The ratio of the number of the completed tasks to the total number of tasks equals the completion rate of the network tasks. For example, the node 7 is the destination node and the number of sensor nodes (excluding destination nodes) is 12, then the task completion rate is equal to the ratio of the value of sum of the seventh column elements in the reachability matrix minus the value of y_{77} to the total number of tasks (that is, 12). If $\theta \leq 0.8$, the network is considered to fail, $N_f = N_f + 1$.

Step 7: If $j < N_S$, turn to the step 3, or $j \geq N_S$, output the number of the network failures and the reliability of monitoring network.

Through N_S simulations, the number of network failures N_f can be achieved. The failure rate η and reliability R of the monitoring network are described respectively as eq.(10) and eq.(11):

$$\eta = \frac{N_f}{N_S} \times 100\% \tag{10}$$

$$R = 1 - \eta = \frac{N_S - N_f}{N_S} \times 100\% \tag{11}$$

IV. Simulation analysis

The reliability of the monitoring network can be classified as intra-cluster reliability and overall reliability. The topology of sensor networks of each blade (i.e., intra-cluster networks) has great influence on the intra-cluster reliability and overall reliability of the network. Generally, there are three different types of topologies for wireless sensor networks [18], including star network, tree network and mesh network. Compared with the star network, the tree network and the mesh network topologies are more flexible, more reliable and more conveniently to be expanded. Thus, they are better suited for the monitoring network of the wind turbine blade. Actually, the tree network and the mesh network have their own advantages and disadvantages which are listed in Table 1. Besides, the performance of the tree network and the mesh network will also change with the different number of sensor nodes, which will be discussed in the following simulation. In this paper, the intra-cluster tree network and intra-cluster mesh network are simulated by the above Monte Carlo reliability evaluation method and the intra-cluster reliability and overall reliability of the network with different number of intra-cluster nodes are obtained. Then, the topology selection principle of sensor network for a single blade is given. Furthermore, the influence of the maintenance cycle and bit error rate on the overall reliability of the monitoring network is analyzed.

Table 1 Advantages and disadvantages of tree network and mesh network

Network type	Advantages	Disadvantages
Tree network	flexible, extensible and high reliable	high dependence on each other
Mesh network	high reliable transmission because of great redundancy of communication links	complex, large energy consumption and short lifetime

A. *The intra-cluster reliability analysis of monitoring network*

The lifetime of sensor nodes obeys the Weibull distribution defined by eq.(1). The values of λ and k can be obtained by parmhat=wblfit (data) function in MATLAB R2014a and "data" represents sample values. Taking the intra-cluster tree network for example, lifetimes of 20 sensor nodes are provided by the wireless sensor manufacturer and listed in Table 2. The values of λ and k can be obtained by putting the 20 lifetimes into parmhat=wblfit (data) function in MATLAB R2014a, then the results are: $\lambda_1=10^6$, k_1=4. The expected value of lifetime is 10^6h. Similarly, according to the lifetimes of 20 sensor nodes of the intra-cluster tree network listed in Table 3, the results are: $\lambda_2=10^5$, k_2=4. Bit error rate of data transmission P_{bit} , maintenance cycle T and data frame length l of physical information of wind turbine blades are respectively set to 0.2×10^{-4}, 1300h and 65×8bit. Simulate the intra-cluster reliability of tree and mesh networks respectively by Monte Carlo method and the number of simulation times is set to 30000.

Table 2 Lifetimes of 20 sensor nodes of the intra-cluster tree network /(10^6h)

1.1399	0.7640	1.2710	1.0997	0.6910
0.7069	0.9256	1.3028	1.2745	0.8109
0.5623	1.1078	0.5212	0.9197	1.2336
0.7610	0.5625	0.9191	0.8982	0.6870

Table 3 Lifetimes of 20 sensor nodes of the intra-cluster mesh network /(10^5h)

1.1892	1.1019	0.7819	1.1609	0.8935
1.0402	0.8797	0.7068	0.8936	0.6887
0.7890	1.2357	1.1380	1.2079	0.6230
0.5504	0.5422	0.5112	1.1580	1.1712

1) *Intra-cluster reliability simulation of the intra-cluster tree network*

Taking Fig.4 for example, the topology of the designed sensor network is the tree network. The solid lines represent the communication links and the communication between two adjacent nodes on the same communication link is unidirectional. In this network, the repeated transmission of information and the energy consumption can be effectively reduced. There are 13 nodes in the network. The node 7 is the cluster head node which is also the destination node. In the initial condition, the sensor nodes and the communication link are normal. The initial adjacency matrix A is the following:

$$A=\begin{bmatrix} 0&1&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&1&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&1&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&1&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&1&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&1&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&1&0&0&0&0&0&0\\ 0&0&0&0&0&0&0&0&0&0&1&0&0\\ 0&0&0&0&0&0&0&0&0&0&0&1&0 \end{bmatrix}$$

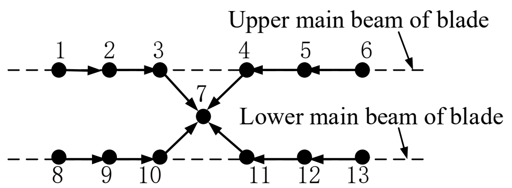

Fig.4 Intra-cluster tree network

It can be found that the number of failures of the intra-cluster tree network N_f is 2138 in the 30000 simulations and the reliability R is 0.9287. Take some simulation in which the node 3 fails and other nodes are normal for example. Solve the reachability matrix Y. According to Y, it can be found that the data of node1, node 2, node 3 cannot be transmitted to the destination node 7 and the completion rate of tasks is θ=9/12=0.75≤0.8, thus the network fails.

2) *Intra-cluster reliability simulation of the intra-cluster mesh network*

Taking Fig.5 for example, the topology of the designed sensor network is the mesh network. The solid lines represent the communication links. The communication between two adjacent nodes on the same communication link is bidirectional and the adjacency matrix is symmetric. There are 13 nodes in the network. The node 7 is the cluster head node who is also the destination node. There are multiple paths for each intra-cluster node to transmit information to the destination node, thus the reliability is higher. In the initial state, the sensor nodes and the communication link are normal. The initial adjacency matrix A is as follows:

$$A=\begin{bmatrix} 0&1&0&0&0&0&0&1&1&0&0&0&0\\ 1&0&1&0&0&0&0&1&1&1&0&0&0\\ 0&1&0&1&0&0&1&0&1&1&0&0&0\\ 0&0&1&0&1&0&1&0&0&0&1&1&0\\ 0&0&0&1&0&1&0&0&0&0&1&1&1\\ 0&0&0&0&1&0&0&0&0&0&0&1&1\\ 0&0&1&1&0&0&0&0&0&1&1&0&0\\ 1&1&0&0&0&0&0&0&1&0&0&0&0\\ 1&1&1&0&0&0&0&1&0&1&0&0&0\\ 0&1&1&0&0&0&1&0&1&0&1&0&0\\ 0&0&0&1&1&0&1&0&0&1&0&1&0\\ 0&0&0&1&1&1&0&0&0&0&1&0&1\\ 0&0&0&0&1&1&0&0&0&0&0&1&0 \end{bmatrix}$$

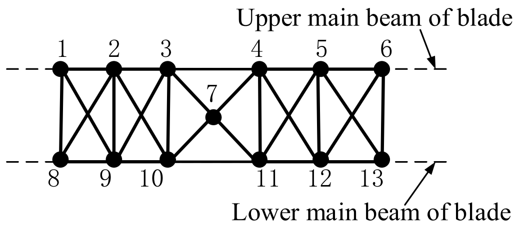

Fig.5 Intra-cluster mesh network

It can be found that the number of failures of the intra-cluster mesh network N_f is 261 in the 30000 simulations and the reliability R is 0.9913. Take some simulation in which the node 3 fails and other nodes are normal for example. Solve the reachability matrix Y. According to Y, it can be seen that only the data of node 3 cannot be transmitted to the destination node 7 and the completion rate of tasks is θ=11/12=0.92≤0.8, thus the network is normal according to the reliability evaluation criteria of the monitoring network.

B. The influence of the number of intra-cluster nodes on the intra-cluster reliability

In view of the cost, the number of sensors deployed on a single blade should not be too large in practical application. In this paper, the number is set to [5,45]. Simulate the reliability of the intra-cluster network in which the number of intra-cluster sensor nodes is from 5 to 45 by Monte Carlo method. The intra-cluster reliability of the intra-cluster tree network and the intra-cluster mesh network with different number of nodes is shown in Fig.6.

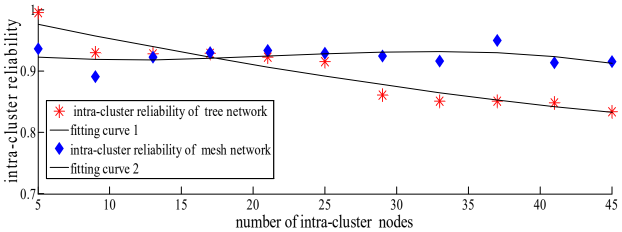

Fig.6 The changes of intra-cluster reliability with the number of nodes

Based on the above simulation results, the selection principle of the network topology for each blade is proposed as follows. Firstly, achieve the relationship between the intra-cluster reliability and the number of nodes of the two topology networks by Monte Carlo method. Secondly, choose the topology with greater reliability as the final measure. As shown in Fig.6, when the number of nodes is less than 16, the intra-cluster reliability of the tree network is better than that of the mesh network. When the number of nodes is greater than or equal to 16, the intra-cluster reliability of the mesh network is almost unchanged and the intra-cluster reliability of the tree network decreases obviously. In this paper, the number of sensor nodes of a single blade is 13, thus the tree network is adopted to established the monitoring network.

C. The influence of maintenance cycle and bit error rate on the overall reliability of the monitoring network

Because the overall reliability of the condition monitoring network of the wind turbine blade changes with the maintenance cycle, it is necessary to discuss the influence of maintenance cycles on the overall reliability to formulate a reasonable maintenance strategy. Due to the utilization of wireless communication in the monitoring network, problems of packet loss and so on are inevitable because of the communication interference in the actual operation. The bit error rate of data transmission is different, thus the different communication interference environments can be simulated by setting different bit error rate. In our work, the overall reliability of monitoring network is simulated by Monte Carlo method.

The overall reliability of the tree monitoring network with 13 intra-cluster nodes and 3 clusters is simulated to research the influence of the maintenance cycle and bit error rate on the overall reliability of the network. In the simulation, the maintenance cycle is set to [0, 10^4]h and the bit rate P_{bit} of data transmission is set to [10^{-6}, 10^{-2}]. The simulation result is shown in Fig.7. It can be found that the overall reliability of the condition monitoring network of the wind turbine blade decreases with the increase of maintenance cycle. The maintenance cycle of the condition monitoring network of the wind turbine blade should be less than 4000h to ensure that the overall reliability of the monitoring network is more than 0.9. When the bit error rate of information transmission is in [10^{-6}, 10^{-4}], the overall reliability of the monitoring network changes little and is mainly determined by the maintenance cycle. When the bit error rate is greater than 10^{-4}, the overall reliability decreases rapidly. When the bit error rate is 10^{-3}, the overall reliability is attenuated to nearly 0. Thus, bit error rate becomes the main factor affecting the overall reliability of the monitoring network. In order to improve the overall reliability of the monitoring network, the data retransmission measure can be adopted.

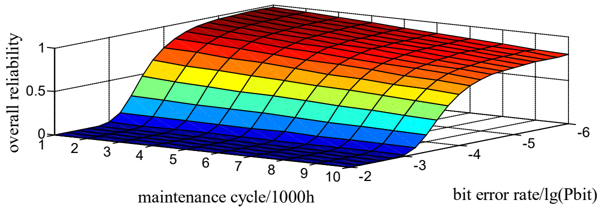

Fig.7 The changes of the overall reliability of the monitoring network with the maintenance cycle and bit error rate

V. THE DATA RETRANSMISSION MEASURE

As mentioned above, the communication link become the main factor that restricts the overall reliability of the monitoring network with large communication interference. In this section, the solution to communication link failures is proposed based on the data retransmission measure, that is, if the links fail the data frames will be retransmitted.

There are 3 clusters in the monitoring network of the wind turbine blade and 13 sensor nodes in each cluster. The changes of the overall reliability of the monitoring network with the number of intra-cluster sensor nodes before and after adopting the one-time data retransmission measure are achieved by Monte Carlo method, as shown in Fig.8. It can be found that the overall reliability of the monitoring network can be effectively improved by adopting the data retransmission measure and the overall reliability remains generally stable with the increase of the number of sensor nodes.

In order to evaluate the role of data retransmission measure in communication anti-interference, the bit error rate of information transmission of the monitoring network is set to [10^{-6},10^{-3}]. The overall reliability of the monitoring network is simulated under no data retransmission, one-time data retransmission and two-time data retransmission respectively. The results are shown in Fig.9. It can be found that the overall reliability of the network changes little before and after the data retransmission measure being adopted when the communication interference is small, i.e., the data bit error rate is small. However, when the communication interference is large, the overall reliability of the monitoring network with no data retransmission decreases rapidly, which is obviously inferior to that of the monitoring network with data retransmission. Compared with the one-time data retransmission, the improvement of overall reliability of the monitoring network with two-time data retransmission is little and the communication cost is increased. Therefore, it is more appropriate to adopt the one-time data retransmission measure.

Aiming at the failure of sensor nodes in the monitoring network, it can be solved by deploying several spare wireless sensor nodes. That is, when a sensor node fails, the nearby spare node will replace it. Thus, the reliable operation of the monitoring network can be guaranteed. This part of work will be the focus of our further study.

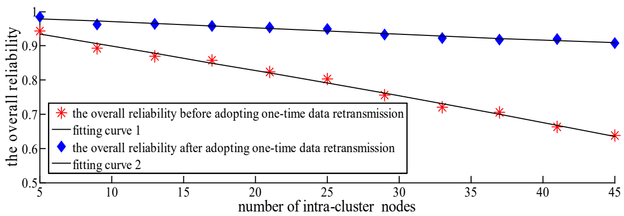

Fig.8 Changes of the overall reliability of the monitoring network with the number of intra-cluster sensor nodes before and after adopting the one-time data retransmission measure

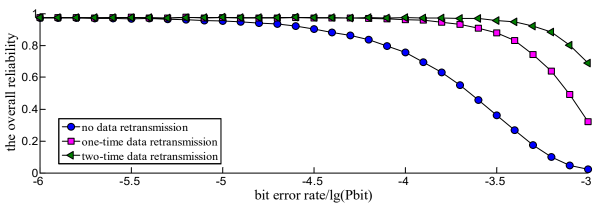

Fig.9 The role of data retransmission measure in communication anti-interference

VI. Conclusion

This paper discusses the reliability analysis method of the condition monitoring network for the wind turbine blade based on wireless sensor networks. Two critical factors, the reliability of sensor nodes and the reliability of communication links are involved in our study. The method of reliability evaluation for monitoring network is proposed based on Monte Carlo method. According to the simulation results, the selection principle of the sensor network topology for each blade is presented. An appropriate maintenance cycle is achieved by analyzing the influence of maintenance cycle and communication interference on the overall reliability of the network. Meanwhile, the overall reliability of the network can be improved effectively by adopting the one-time data retransmission measure.

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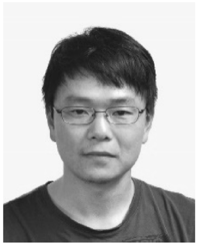

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